

## **Survey of Temperature Measurement Techniques For Studying Underwater Shock Waves**

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### **Abstract**

Several optical methods for measuring temperature near underwater shock waves are reviewed and compared. The relative merits of the different techniques are compared, considering accuracy, precision, ease of use, applicable temperature range, maturity, spatial resolution, and whether or not special additives are required.

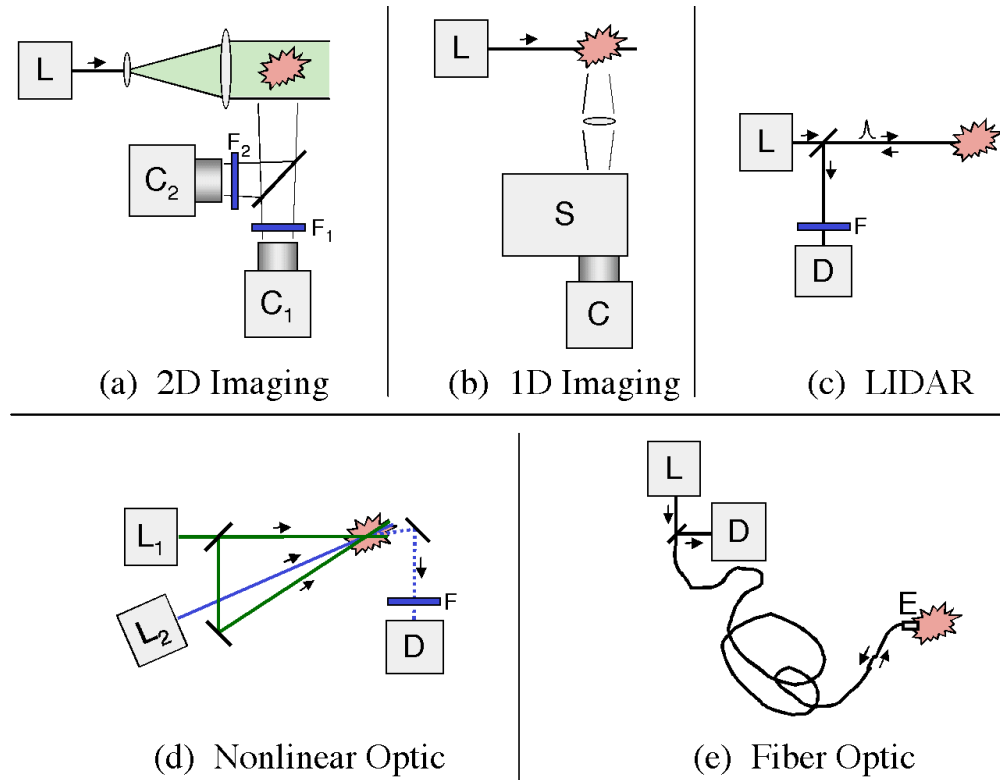
### **Introduction**

Shock waves are used or have potential for use by the medical community to treat a variety of different ailments. Extracorporeal Shock Wave Lithotripsy (ESWL) routinely used to break up calcium deposits and kidney and bladder stones.<sup>1</sup> In fact, ESWL is today used to treat about 85% of all kidney stone cases.<sup>2</sup> Shock waves have potential to treat various types of cancers non-invasively, through the process known as hyperthermia.<sup>3</sup> These shock waves are generated by various methods, most often using explosive charges. Pressures on the order of hundreds of bars can be achieved over focus areas of a few to tens of mm long. These devices, when placed against human tissue, direct a strong shock wave at the target object that interacts with the object, such as in breaking up of calcium deposits. New shock-wave-generating devices are commonly studied in liquid water. If they show promise, then trials are made in dead or live (animal) tissue, and if they show further promise, trials can be made in humans. It is relatively commonplace to measure the pressure increases associated with these generated shock waves by using a hydrophone. The pressure rise is used as an indication of the performance of a shock wave generating device.

These shock wave generating devices also heat the tissue. This can have negative consequences if the heating damages tissue nearby the target area. On the other hand, this heating can be harnessed to treat certain types of cancers. In a method known as hyperthermia a tumor is locally heated by  $\sim 10^\circ\text{C}$  above body temperature for up to an hour. This temperature rise kills and/or shrinks cancerous tissues while leaving healthy tissues intact. Ultrasound-induced cell death has been studied for treating cancers of the prostate, liver, brain, bladder, breast and heart. Some ultrasonic hyperthermia treatments, including one that targets prostate cancer, have been approved and have become available in the past few years.<sup>3</sup> Yet, using shock waves for hyperthermia treatment is still a very active research area.

The coupling of shock wave energy into the human body has other applications. If the waves are focused to heat tissues by tens of  $^\circ\text{C}$  then the tissue coagulates in a few seconds. This method can be used to kill tissue, or to close blood vessels. The shock waves can also be used to ablate (vaporize) tissue. These treatments are non-surgical and have several benefits including fast treatment, reduced complications compared to drug-based therapy, reduced risk of infection compared to surgery, and short recovery time.

In the case of shock wave generators, it is very important to understand the mechanism by which the temperature of the sample is increased. Thermocouples, which have slow response, can be used to measure the net temperature increase. However, thermocouples can interact with the shock wave, so non-intrusive measurement techniques are desirable. Furthermore, since the speed of shock waves in water is very high ( $>1500\text{ m/s}$ ) very fast time response is also desirable. To our knowledge, the fastest commercial probe-type thermocouples (Omega Engineering, Inc.) have response times of a few milliseconds in air and hundreds of milliseconds in liquid water. However, the pressure peaks associated with shock waves in liquids typically have widths  $<1$  microsecond. A temperature measurement technique with a time response of a few hundred nanoseconds or better is thus desired to probe these shock waves, allowing the time history of the temperature to be more fully characterized.



**Figure 1.** Five different experimental arrangements that can be used to measure temperature of water using advanced optical diagnostics. The symbols L, F, C, D, S, and E represent laser, filter, camera, detector, spectrometer and etalon, respectively. Subscripts are used to differentiate between two different pieces of equipment in the same setup. The irregular shaped blob is the region of interest of the measurement.

This paper reviews a variety of different optical measurement techniques that show promise for measuring the transient temperature response generated by shock waves in liquids. The review is not exhaustive, but rather is intended to be illustrative of the variety of measurement techniques available in the literature that could potentially solve this response time problem. It is assumed that measurements will be carried out in liquid water held in a container having good optical access from all sides.

### Characterization of Measurement Setups

There are five types of measurement schemes described herein, sorted by optical arrangement, shown in Figure 1. The first type of measurement setup is a traditional two-dimensional imaging scheme in which a laser sheet is directed into the region of interest. Depending on the color of the laser light and the contents (additives) in the water, some of the light is either scattered or absorbed and emitted as fluorescence. Typically a camera placed perpendicular to this laser sheet will image the illuminated region. The camera captures the scattered or emitted light and an image is formed. In order to measure temperature, some temperature-dependent property of the scattered light must be understood and measured. In many cases, the spectrum of the scattered or emitted light changes with temperature. In this case, a spectral filter (F1) may be placed in front of the camera to sense this change. In practical use, a reference image without the filter must also be acquired so that changes in measured intensity can be ascribed to temperature variations instead of variations such as laser sheet energy. A second camera is often used for this purpose; the second camera views the same region through a beam splitter. Additionally, a second spectral filter (F2) can also be placed in front of this second camera.

Imaging schemes like those shown in Figure 1(a) generally have coarse spectral resolution that is limited by the filter. While this coarse spectral resolution may be suitable in some applications, better spectral resolution can often be obtained by using the schematic shown in Figure 1(b). Here, a one-

dimensional line of the flow is imaged through the spectrometer onto the camera; improved spectral resolution has been obtained at the cost of reduced spatial resolution. This approach often can produce more accurate results than the 2D approach since more spectral data is obtained.

A third scheme is shown in Figure 1(c). This is known as a Light Detection And Ranging (LIDAR) setup. Typically a short pulse of light is emitted from the laser source and directed into the region of interest. Some interaction with the liquid occurs and scattered or emitted light returns to the detector. The time delay is used to compute the “range”, that is the distance of the measurement location from the detector. The temperature is typically measured from the spectrum of the detected light. The spectrum can be measured either through spectral filters or a spectrometer.

A fourth scheme is a nonlinear optical scheme, shown in Figure 1(d). Nonlinear optical schemes typically use three input laser beams, which may originate from different laser sources. These beams are usually crossed and focused at the point of interest in the flow. An interaction between these three beams and the liquid generate a fourth laser beam that is detected. This fourth beam is analyzed, either in the time domain or spectrally to determine the temperature of the liquid at the crossing point.

A fifth and final scheme shown in Figure 1(e) uses fiber optics. Fiber optics, while not entirely non-intrusive (they can interact with the flow) offer potential advantages for measuring temperature behind shock waves in liquids, and will be discussed accordingly. A unique advantage of the fiber-optic method is that it could be used in live tissues by insertion with a hypodermic needle.

These schemes will be referred to in subsequent sections as: *2D imaging*, *1D imaging*, *LIDAR*, *nonlinear optical* and *fiber optic*. Several different physical principles that use these schemes to measure temperature will be evaluated in the next section. The evaluations will consider the ability of the technique to determine temperature accurately with fast time response. Other criteria of importance include degree of advancement of the technique, ease of use, spatial domain of the measurement, ability to make single-shot measurements, and whether exotic additives are required.

## Measurement Techniques

In this section, the physics of the optical process involved in the different techniques are described. In many cases, the same physical phenomena can be implemented by several of the optical measurement schemes described in the previous section.

### *Raman Scattering*

A small fraction of light incident upon a liquid will scatter from it inelastically (at a slightly different color). The difference in energy between the incident and scattered photons is either absorbed or liberated by the probed molecule. The shifted light, which contains information about the liquid, can be detected and analyzed to determine the composition and temperature at the measurement point. This process is known as Raman scattering. In the case of liquid water, the Raman spectrum is in the 3000 to 4000  $\text{cm}^{-1}$  spectral region. This originates from OH vibrations in the water molecule.<sup>4</sup> The spectrum of the Raman scattered light changes with temperature, and so can be used to measure the temperature of liquid water remotely.

In reference 5, Raman scattering was implemented using the 1D-imaging scheme shown in Figure 1(b). A high powered (10 Watt) continuous-wave argon-ion laser was used to generate Raman scattering. The scattered light was dispersed onto a CCD camera so that one axis contained the spectrum and the other axis contained spatial distance. The measured time-averaged spectra were best fit to obtain temperature, with an accuracy of 2 °C in comparison with a thermocouple. Measurements were performed over a range from 30 to 100 °C. In a similar liquid water Raman experiment,<sup>4</sup> a pulsed laser was used in a LIDAR configuration. Temperature was measured over a temperature range from 3 to 40 °C with a ~2 °C accuracy. In the first experiment, measurements were averaged for an unspecified duration. In the second, 500 individual laser pulses were averaged. Thus, the ability of this method to measure temperature instantaneously has not yet been demonstrated to our knowledge. Raman scattering is generally very weak, which is why such high-powered lasers are required and why measurements are averaged over many seconds or many pulses. In order to measure unsteady events such as shock waves, instantaneous measurements are preferred. Nonetheless, if a repetitive shock wave device that can be timed precisely can be used, then this technique holds promise to make reliable temperature measurements in liquid water.

This method has certain advantages when compared to other techniques. It has the advantage that a line in the flow can be imaged as opposed to measuring just a single point. This line could be oriented in the same direction that the shock wave propagates. However, the timing would need to be precisely controlled so that timing jitter would not smear out the peak of the measured temperature profile. Another advantage is that this method can be extended to the 2D imaging scheme, albeit with a lower demonstrated accuracy of 5 °C.<sup>6</sup> Another advantage of this technique is that additives are not required, as is the case in some methods described below. Finally, this method is a direct measure of temperature, as opposed to a method that infers temperature from another measured property.

### *Brillouin Scattering*

Using the LIDAR configuration shown in Figure 1(c), the backscatter from a high-powered, narrow-linewidth, pulsed YAG laser directed into water can be measured. This back-scattered light is Brillouin scattering (scattering of light from acoustic waves in the medium). It is predominantly split into two frequency-shifted lines centered symmetrically about the laser frequency. The spacing of these lines depends on the sound speed, which is temperature dependent. Very high-resolution molecular filter(s) can be placed in front of the detector(s) to measure the spectral separation between these two peaks, thereby determining the sound speed or temperature.<sup>7</sup> Preliminary measurements have been reported in liquid water over a range from 2 to 36 °C. These indicate a linear relationship between known temperature and the ratio of two detectors monitoring different components of the Brillouin spectrum. These show good potential for accurate measurements in liquid water.<sup>8</sup>

Unfortunately, in the existing demonstrated configuration, this measurement technique would not be suitable for measuring temperature near underwater shock waves. The main difficulty is in ranging: the depth resolution in the current experiment is about 1 meter.<sup>8</sup> To obtain depth resolution on the order of 1 mm, which would be comparable to other measurement techniques, the laser pulse duration would have to be reduced by three orders of magnitude to 10 ps. But, such a short pulse would have a spectral linewidth greater than 1 cm<sup>-1</sup> owing to the Fourier transform limit. This spectral width would smear out the Brillouin shift, which is typically a fraction of 1 cm<sup>-1</sup>. To overcome this limitation, the same technique could be used in the 2D imaging configuration shown in Figure 1(a). The cameras would then provide good spatial resolution. Drawbacks associated with this approach are that it has not yet been demonstrated, it uses a relatively hard-to-obtain isotope of iodine (<sup>129</sup>I), and that it is primarily a measure of sound speed; temperature must be inferred from this. It is presently unclear whether this method would produce sufficient signal to obtain single-laser-pulse measurements, but it is certainly possible: in gases Rayleigh-Brillouin scattering is typically a few orders of magnitude stronger than Raman scattering. Another advantage of this method is that it does not require additives.

### *Laser-induced fluorescence*

If a liquid absorbs incident light from a laser beam and subsequently emits that light as fluorescence then this fluorescence may be sensitive to temperature. However, we have not found any papers utilizing the natural fluorescence of liquid water to measure temperature. Instead, there is an abundance of literature in which fluorophores and other tracers have been added to liquids so that absorbed laser light will fluoresce brightly and will allow temperature to be measured accurately.<sup>9</sup> One technique that has been developed involves using the temperature-sensitive quantum yield (ratio of emitted to absorbed photons) of the fluorescence.<sup>9</sup> The absolute signal intensity can then be related to temperature. In practice this is difficult to accurately quantify because of the calibrations required and because variations in concentration of the active species or laser intensity lead directly to temperature measurement errors. Another method takes advantage of the shift with temperature in the peak wavelength of the fluorescence (i.e. thermochromic shift). Because these thermochromic shifts are small, and therefore hard to measure, the temperature sensitivity is typically limited to applications having temperature changes of 10 °C or more.<sup>9</sup>

A sensitive method of performing laser-induced fluorescence thermometry in liquids has been developed that uses fluorescent emission from molecular complexes. An excited species can form a complex with another molecular species in its ground state and then emit a photon. This so called “excimer emission” is at a different wavelength than the “monomer emission” from the species itself. The ratio of excimer to monomer emission is temperature sensitive. Since the fluorescence from the two different emission bands are well separated spectrally, a 2D imaging scheme, shown in Figure 1(a) can be used to

make 2D maps of temperature. Bipyrenyl fluorophores have been used to measure temperature with a precision of about 1 °C over a range of approximately 0 to 60 °C. Because these fluorophores emit brightly, it is expected that temperature could be measured in a single-shot, though to our knowledge this has not yet been demonstrated.

Advantages of this method compared to the others described in this paper include experimental simplicity, and good signal intensities leading to the ability to make single-shot measurements. Also, it is a direct measure of temperature. Disadvantages include the fact that fluorophores must be added to the water and that single shot measurements have not yet been demonstrated to our knowledge.

#### *Laser-induced thermal acoustics*

In collaboration with the Shock Wave Research Center at Tohoku University in Sendai, Japan, we have recently developed a temperature measurement technique based on laser induced thermal acoustics (LITA).<sup>10</sup> This is a nonlinear optical measurement technique that has previously been used at NASA Langley Research Center and elsewhere to measure temperature and velocity in gases with good accuracy.<sup>11</sup> A highly simplified diagram of this measurement scheme is shown in Figure 1(d). Two beams generated by the same pulsed laser are focused and crossed at a point. These two beams generate a strong interference pattern that creates counterpropagating acoustics waves in the medium through an electrostriction process. A third beam incident upon these counterpropagating waves is scattered into a 4<sup>th</sup> beam. The scatterings from the two acoustic waves are at slightly different frequencies, so they beat together when they are detected. The measured beat frequency depends on the speed of sound of the gas at the beam-crossing region. We have adapted this method to measure the sound speed, and hence temperature in liquid water.

We performed measurements in a static rectangular tank filled with water. The water was heated using a series of resistance heaters oriented around the laser beams. The temperature of the water was simultaneously measured with a thermocouple. Measurements were performed between 10 and 70 °C. Our experiments indicated that temperature could be measured with an accuracy of 1.5 °C and a single shot precision of 4 °C over the range of 10 to 45 °C. These measurements were made with a time resolution of about 300 ns and a spatial precision of about 0.2 mm x 0.5 mm x 10 mm.

This method could be improved in a straightforward manner by using a shorter pulse duration laser such as a 100 ps laser. This would allow the beam crossing angle to be increased by a factor of 5 or more resulting in a corresponding factor of 5 improvement in temporal resolution, perhaps down to 60 ns or better. Also, the spatial resolution could be improved to roughly 0.2 mm x 0.2 mm x 0.5 mm or better. Making these changes would not compromise the accuracy of the technique. In fact, by sampling more oscillations, measurement precision could be improved at the expense of time response.

Advantages of the LITA technique are that it has been proven to make single-laser pulse measurements with good accuracy and fast time response. As demonstrated, the spatial resolution was marginal, though this effect could be mitigated by orienting the direction of the shock wave motion to be in the direction of the best spatial resolution. Still, using a picosecond pump laser would allow substantial improvements to the time response and spatial precision. Disadvantages of the method are that it is a single-point measurement so a repetitive shock-generating system would be required to map out the temperature response; also LITA does not directly measure temperature, instead inferring temperature from measured sound speed.

#### *Fiber optic probe*

A small, fast fiber-optic temperature-measurement probe has recently been developed.<sup>12</sup> This probe consists of an optical fiber that delivers light to a very small Fabry-Perot etalon attached to the tip of the fiber. The spacing of the mirrors on the etalon depends on temperature; this spacing can be precisely measured by monitoring the reflected light. This type of probe is known as an Extrinsic Fabry-Perot Interferometer (EFPI) sensor. Whereas thermocouple junctions are connected to wire which is conductive, the optical fiber is an insulator, meaning that heat conduction is small. Since the sensing element is very small (100 microns diameter x 40 micron length with mass as low as 0.15 micrograms) and there is negligible heat conduction, the time response of the sensor is very fast. In a suitably hot environment, such as excitation with a high-powered pulsed laser, this sensor has been demonstrated to respond at up to

$2.4 \times 10^6$  K/sec, determined with a sampling rate of 500 kHz. For small temperature rises, this corresponds to sub-microsecond response times which is faster than most thermocouples, but still may not be fast enough to respond to shock waves in liquid water.

Advantages of this fiber optic method include simplicity and ease of use, large operating range (0-1400 °C demonstrated), good accuracy (0.16% of full scale, or  $\sim 2$  °C), and the ability to use this probe in live tissue by inserting with a hypodermic needle. Despite the fact that this method measures temperature at a single point, it is possible that it could do so repeatedly with sub-microsecond time response (though this has not been demonstrated yet), thereby measuring the time history of the shock wave in a single event. Disadvantages of this method are that it is very new and relatively untested, that the time response may not be fast enough, and that it is a physical probe and may therefore interact with the shock wave. Also of concern is that the rise time of this sensor was demonstrated to be fast, but the fall time was more than an order of magnitude slower, though it is thought that this limitation can be overcome.<sup>12</sup>

Technique	Time Resp.	Temp. Range [C]	Temperature Accuracy [C]	Spatial Extent	Spatial Resolution	Ease of Use	Demonstrated Single Shot	Additives
LITA	300 ns	10-45	1.5	Point	40 mm x 0.2 mm or better	Hard	Yes	No
Fluorescence: Excim./Mono.	?	0-60+	1	1D or 2D	<0.2 mm	Moderate	No	Yes
H <sub>2</sub> O Raman	?	3-100	2	1D or 2D	<0.2 mm	Moderate	No	No
Brillouin LIDAR	?	2-36	?	Point	10 cm	Moderate	Yes	No
Fiber Optic	$\sim 1 \mu s$	0-1400	2	Point	$\sim 0.2$ mm	Easy	Yes in air, not water	Fiber must be inserted

**Table 1.** Summary of some relevant parameters for consideration in comparing temperature measurement techniques for studying shock waves in liquid water. Note that this comparison is not exhaustive and some of the entries are the opinions of the authors. Cells containing “?” indicate that this data was not provided in published reports.

## Discussion

Table 1 summarizes some of the relevant parameters characterizing the demonstrated performance of the different temperature measurement techniques. It is presently unclear which technique is the most suitable for measuring the transient temperature response behind shock waves in liquids. None of the methods are “turn-key” solutions that would be guaranteed to provide the required results. All of these methods require further development and experimentation before they would be suitable to produce reliable measurements.

Still, some general comments about the techniques and comparisons between them can be made. In general single-shot techniques are strongly preferable to time-averaged methods, particularly when studying shock waves. Time-averaged methods require the shock wave event to be repeated precisely. This is very difficult to accomplish particularly when explosive charges are used because of the orientation and dynamics of the explosion process. In this regard, the laser-induced fluorescence technique, the Brillouin scattering and maybe the fiber-optic measurement techniques are preferable. The LITA method is “single shot” but since it is also a single-point method that cannot make measurements in rapid succession, the flow under investigation also is required to be precisely repeatable.

There are significant drawbacks for two of these techniques (Brillouin and LITA), which measure sound speed and then determine temperature by inference. The first problem is that, in water, as the temperature increases from 0 °C the sound speed increases with temperature, and then reaches a maximum at about 75 °C, and then decreases. Thus, above about 65 °C sound speed is very insensitive to temperature. In fact, the curve is dual-valued: one value of sound speed corresponds to two different temperatures. This limits the dynamic range of temperature measurements based on sound speed. This problem can be overcome by using other liquids that may not have a dual-valued relationship between sound speed and temperature. Another complication is that at pressures above 100 bar, the sound speed depends on pressure as well as temperature. Thus, for strong shock waves, it is not possible to directly relate measured sound speed to temperature. This error is small at pressures  $\ll$  100 bar, but can be on the

order of a few degrees or more near 100 bar. Thus, methods that directly measure temperature are preferable to those that infer temperature from sound speed.

The use of additives such as fluorescing dyes may be undesirable in some applications. These additives can pose health risks, for example. However, if appropriate safety measures are applied, these risks can be mitigated. Alternately, the use of these additives would probably be unsuitable in “in situ” measurements of live tissues. Still, for fundamental laboratory investigations of shock waves, these additives should not cause significant problems.

A final consideration is ease of use. Of the methods described above, considering the experimental hardware setup, software, analysis, etc., the methods can be ranked from simplest to most difficult in the opinion of the author: fiber optic, laser-induced fluorescence, Raman scattering, Brillouin scattering and finally LITA. LITA is extremely difficult to perform because it is a nonlinear optical method that requires very precise alignment and then a weak signal beam (but stronger than Raman) must be detected. Brillouin scattering requires very careful construction and calibration of the iodine absorption cells, which is time consuming. Laser-induced fluorescence on the other hand would be easier to implement, using off-the-shelf lasers, cameras, and optical filter(s). The fiber-optic probe would be easiest of all to use: similar in difficulty to using a thermocouple.

## Conclusion

Based on all of these considerations, we believe that the most promising candidates for further investigation are the laser-induced fluorescence, LITA and fiber-optic methods. While it may prove to be wholly unsuitable in time response, the fiber optic solution would be the easiest to implement (particularly if it can be purchased “off the shelf”) and is therefore recommended for further study. The LITA method is the furthest along in development and therefore has a very high chance to succeed in providing the required data. For example, single-shot temperature measurements with sufficient time accuracy and time response have already been demonstrated. However, in the long run with more study, the laser-induced fluorescence temperature measurement technique could prove to measure temperature easily, accurately, with fast time response, and with good spatial resolution.

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